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INCREASED AFFORDABILITY OF BMD SYSTEMS THROUGH DISTRIBUTED HARDWARE-IN-THE-LOOP DURING DEVELOPMENT

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Abstract

There have been numerous ideas and innovations designed to enhance the affordability of Ballistic Missile Defense (BMD) systems developed in recent years. These innovations include increased use of prototype hardware in the early stages of system development to gain user feedback, perform early evaluations and to provide contingency deployment options. A second innovation is the formulation of capabilities to link various modular types of system simulations and environmental models together to create virtual worlds in which these highly interactive systems can operate. An interesting approach having great potential for yielding more affordable BMD systems combines these two approaches.

The marriage of Hardware-In-The-Loop (HWIL) with distributed simulation technologies allows BMD developers to design and test multiple concepts, improve existing capabilities and evaluate combinations of systems. In addition, this approach tests the system against a wider range of threats and environmental conditions at a lower cost than traditional methods. The end-products of employing Distributed Hardware-In-The-Loop (D-HWIL) technologies are lower developmental cost, fewer problems during operational testing, greater opportunity for reuse across all major Defense Acquisition Programs, and available rapid deployment options.

These D-HWIL capabilities provide a more robust test environment that includes representative numbers of threat objects, plus the composition of friendly forces with which the systems under test would interact. This paper explores the real-world benefits and considerations of utilizing a D-HWIL test tool for existing BMD systems. In addition, the paper also gives considerations for areas where this approach could yield more affordable BMD systems in the future.

Introduction

In order to evaluate BMD system effectiveness, developers must achieve and demonstrate measures of performance by a rigorous, well-defined process involving analysis, simulation, and testing techniques as early in the development process as possible. These activities must quantify and characterize key technical parameters that support the system requirements' verification and performance evaluation process. An important part of this process is the identification of critical issues and shortfalls in system performance early enough in development to allow for cost effective resolutions to occur.

To accomplish these evaluation objectives in the most efficient manner possible, many system developers exercise their prototype HWIL systems in conjunction with constructive, virtual, and live simulations. These prototype HWIL systems support more effective performance assessments by using realistic battlefield configurations with representations of all of the components necessary for integrated system Test and Evaluation (T&E). The most cost effective approach to developing these test tools is to incorporate previously developed tactical system drivers whenever possible. Examples of HWIL systems using this cost effective approach includes; the U.S. Army's PATRIOT Flight Mission Simulator/Digital (FMS/D), the U.S. Air Force Theater Air Command & Control Simulation Facility (TACCSF), and the U.S. Navy AEGIS Combat System Interface Stimulator (ACSIS).

In addition to individual system performance assessments, these prototype HWIL systems are suitable for extending T&E activities to include integration and interface testing with the various other tactical systems within the theater of operations. One of the most promising approaches to accomplish this level of testing is with distributed simulation technology. An excellent

example is available with the development of the Theater Missile Defense (TMD) Family of Systems (FoS).

The Ballistic Missile Defense Organization (BMDO) has directed the development of a TMD System Exerciser (TMDSE) to verify that the TMD FoS can effectively interoperate under realistic battlefield conditions. These TMD systems will be combinations of existing inventory, product upgrades and new systems that evolve to enhance mission effectiveness.

The U.S. Army Program Executive Office-Missile Defense (PEO-MD) is currently beginning the third year of developing the TMDSE for the BMDO. The TMDSE is a test tool that drives geographically distributed, real tactical system hardware and software with a common, synchronized scenario, and evaluates their respective interoperability over tactical communication data nets. The objective of the TMDSE is to stimulate the track processing systems and command and control capabilities of the tactical equipment that will provide the flow of information through the tactical system interfaces. The stimuli for the track processing systems are realistic representations of theater level attack scenarios with defensive actions and counteractions. The resulting information, which flow through the system interfaces, allows for the verification of TMD FoS-level integration and interoperability.

D-HWIL Technology

For over 7 years the Department of Defense (DoD) has been working to define an infrastructure for linking simulations of various types at multiple locations to create realistic, complex virtual environments for large-scale, interactive exercises. The initial accomplishments were mainly because of efforts by the Simulation Network (SIMNET) program managed through both the Advanced Research Projects Agency (ARPA) and the U.S. Army Simulation, Training, and Instrumentation Command (STRICOM). The focus of these initial efforts was mostly on training applications. SIMNET has evolved into the Distributed Interactive Simulations (DIS) technology that is more flexible and robust and supports different types of simulations with different levels of fidelity.

The DIS infrastructure provides interface standards, communications architectures, management structures, fidelity indices, technical forums, and other elements necessary to transform heterogeneous simulations into unified seamless synthetic environments. These synthetic environments support a wide range of uses to include design, prototyping, test and evaluation, and

training. The Institute of Electrical and Electronic Engineers (IEEE) has established Standard 1278 to facilitate commonality in the interface between DIS elements. The DIS standards process addresses the development of architectures, protocols, and message format to support DIS events.

The principle application for DIS is still human-in-the-loop interaction with simulations and the synthetic environment. However, several years ago, the concept developed of combining HWIL with DIS technologies to allow weapon system developers to do early T&E of the TMD FoS. The application of DIS technology to D-HWIL testing represents many engineering challenges due to requirements for very high-fidelity object state data, timing, and data transmission rates. The TMDSE development uses DIS technology; but, also include some other important features discussed below.

The TMDSE concept is to test as much of the tactical equipment, to include hardware, software, and tactical communications as is feasible. The TMDSE tests the tactical system configuration representative of a task force operating in concert as part of a synergistic TMD architecture. This approach provides the user community for these defense systems the depth of evaluation in system-level performance needed to insure mission success.

In June of 1994, PEO-MD demonstrated that the TMDSE concept was obtainable by developing and demonstrating the Proof-of-Principle (POP) configuration. The POP Demonstration connected the Joint Tactical Ground Station (JTAGS) equipment in Azusa, California and the PATRIOT Radar and Engagement Control Station (ECS) in Bedford, Massachusetts to the TMDSE Test Exercise Controller (TEC) in Huntsville, Alabama. The locations of each of the Build 1 participants is shown in Figure 1. During the POP Demonstration, the TEC injected a common, synchronized scenario into these two weapon system platforms in real-time.

The TMDSE Build 1 development expanded the POP capability by adding additional weapon systems as well as new TMDSE components. The new systems included the Navy's AEGIS Weapon System, the Air Force's Talon Shield and Control and Reporting Center (CRC), and the Army's PATRIOT ICC and BTOC / TCS. In addition, the Build 1 enhancements included a more robust dynamic environment consisting of ballistic missile and air breather threats, interceptors, weather, and interceptor and threat debris.

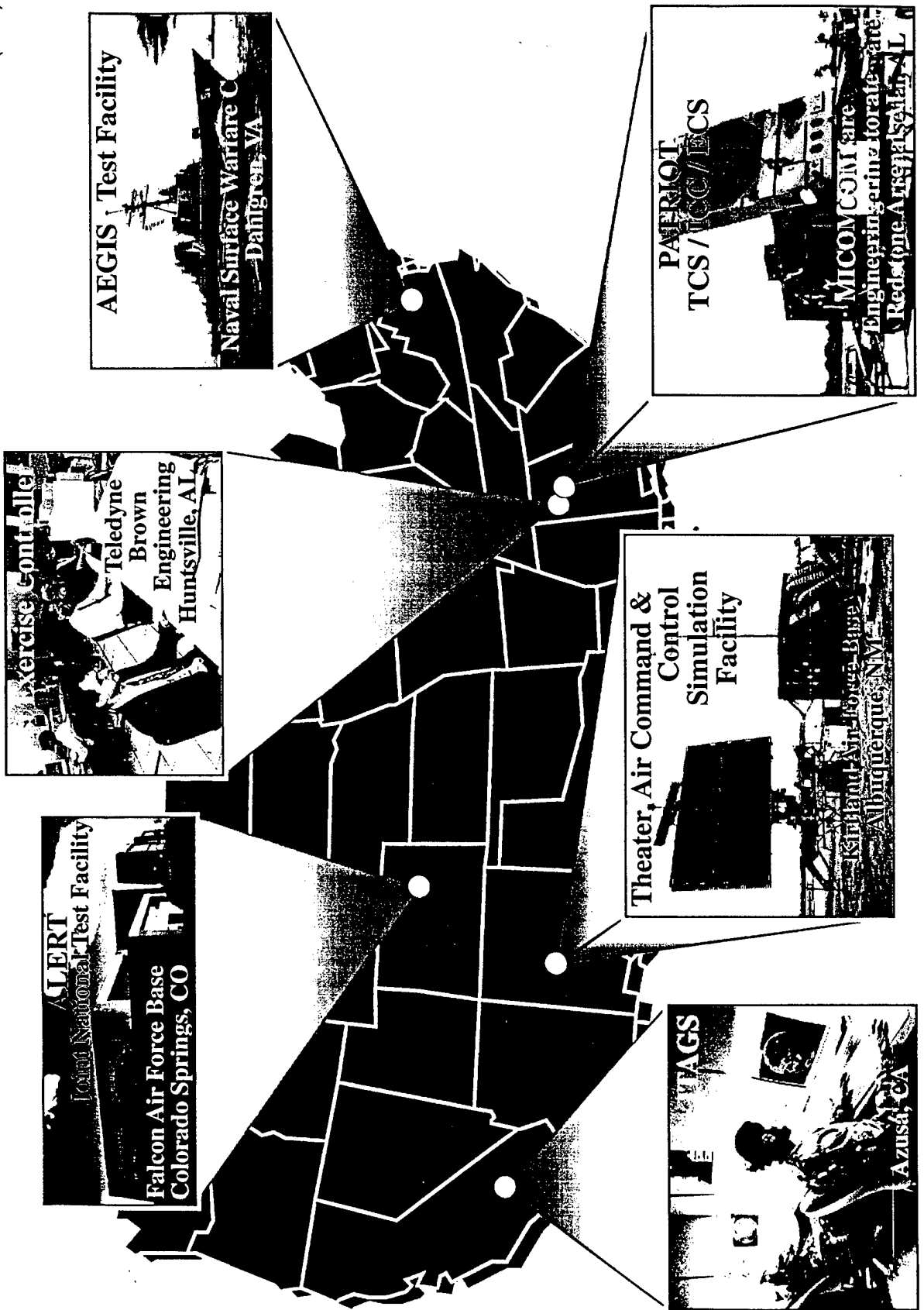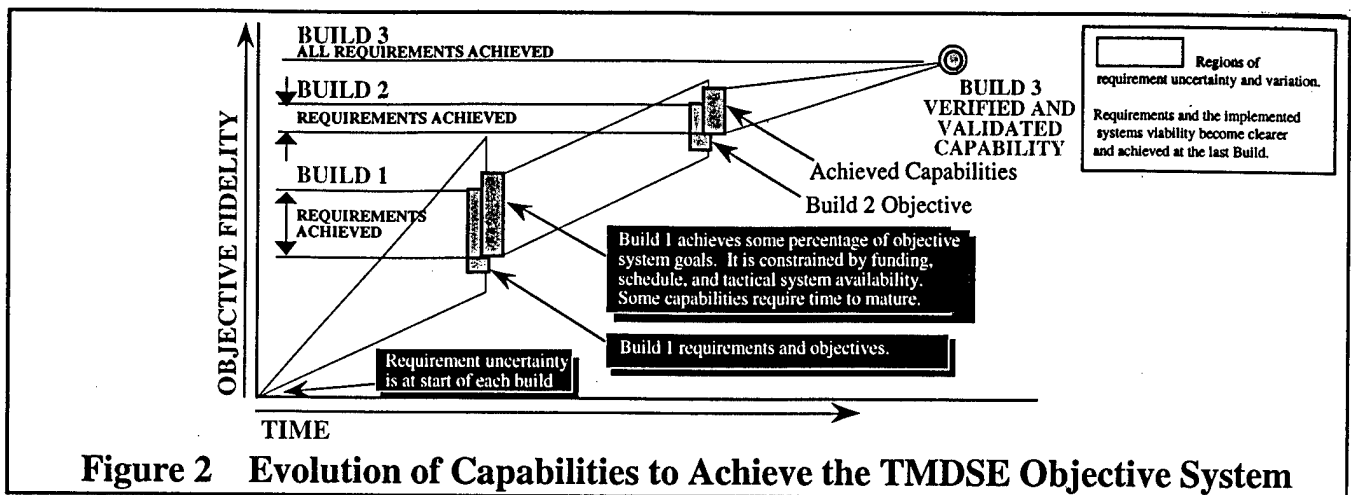Figure 1 TMDSE Build 1 Distributed Configuration

Figure 2 Evolution of Capabilities to Achieve the TMDSE Objective System

The TMDSE development philosophy is a phased, incremental evolutionary approach. Each developmental phase is a "Build". Currently, the PEO-MD is developing the Build 2 configuration. This incremental development methodology embraces the concept of "build a little, test a little" to allow for feedback from the evaluation of each configuration. Each configuration is being evaluated with the TMD users for a full assessment of capabilities and shortfalls. Figure 2 above illustrates the plan for the evolution of TMDSE system capabilities to meet the objective system requirements.

TMDSE D-HWIL Configuration

Each of the respective weapon system Project Offices mentioned above developed drivers to exercise or test their tactical systems during the acquisition process. The capabilities within each driver are unique to the tactical system it supports. Shown in Figure 3 is a summary of the Build 1 tactical system configurations. TMDSE's challenge was to combine these drivers so that they worked in unison to provide a synchronized, coordinated, common, dynamically interactive environment to all the tactical systems being stimulated. TMDSE accomplished this using the TMDSE Control Segment (TCS) which provides the drivers with the threat, environment, and timing data necessary to generate their respective simulated view of the common TCS controlled environment.

The TCS provides the means by which a test operator can configure, execute, and summarize a TMDSE exercise. Configuration of the TMDSE consists of generating data bases, building scenarios, establishing non-tactical communications (voice and data), distributing data, querying the drivers for health and status and initializing all of the drivers. During the preparation and execution phases, the TCS functions include;
- configuration verification
- clock synchronization
- sending object states to the tactical drivers
- collecting data
- receiving and distributing truth data
- dynamic event distribution
- performing quick look analyses during execution
- generating environment data (threat debris, etc.)

At the same time the tactical drivers are responsible for sending interceptor states, interceptor debris, interceptor event status and tactical system perceived data back to the TCS. Following a test or demonstration, the TCS request data collected by the drivers in order to combine and compare it to TCS data and tactical data. The TCS uses these data for various types of analyses supporting specific objectives for development, VV&A, or user evaluation.
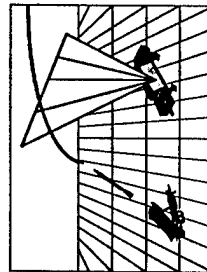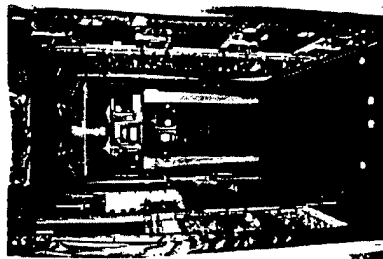
The tactical drivers, although unique to the individual tactical systems they support, provide the interface between the TCS and the tactical system. These tactical drivers are responsible for generating the "scenes" based on inputs from the TCS, that stimulate the tactical track processing systems.

Physically, the TCS consists of the centrally located Test Exercise Controller (TEC) and the Remote Environments (REs) collocated with each Tactical Driver. The TEC connects with each of the REs using High bandwidth data communication links (non-tactical). The REs, in turn, connect to the drivers through a local area network (Ethernet). The driver connections to the tactical systems are unique to the individual systems. Each tactical system uses tactical communications for coordination and execution of tactical procedures. The Build 1 Demo used real Tactical Information Broadcast System (TIBS) and Tactical Related Applications Program (TRAP) Data Distribution System (TDDS) broadcasts, as well as a TADIL-J communications emulator for joint tactical communications.

TCS 960507-02 (6222)

Tactical System Components		AEGIS	PATRIOT	CRC	JTAGS	TALON SHIELD
Tactical Comm		TADIL-J TDDS (not into C2P)	TADIL-J (ICC) TIBS (into TCS) PADIL (internal)	TADIL-J TIBS	TIBS TDDS TADIL-J	TIBS TDDS
Tactical Software Load		5.0.8 with NTDC Extended Range Patch (installed on at least 2 ships at sea)	Tactical Software ECS -PDP4 (V0) ICC - PDP4 (V26) TCS - 3.1.0 (TPW&BCP)	MCE Tactical Software Providing CRC Functionality	Version 10.1.7 Tactical JTAGS Software	Version 10.1.7 Tactical ALERT Software
C2 System Hardware		Baseline 5 Phase 1 Tactical Hardware Configuration (deployed at Sea) • C&D (UYK-43) • C2P (UYK-43) • WCS (UYK-43) • SPY (UYK-43)	Tactical Hardware Configuration • ECS • ICC • TCS (BTOC)	COTS Hardware • EMT • MCE • Correlator	Non-Ruggedized Version of Tactical JTAGS Hardware (Desk Side SG Onix)	Tactical ALERT Hardware (Rack Mounted SG Onix)
Sensor	Back End	SPY1 Digital Data Processor (in SPY)	AN/MPQ-53 Digital Data Processor (in ECS)		Space Based DSPs w/Live (Recorded) Background	Space Based DSPs w/Live (Recorded) Background
Sensor	Front End	Simulated SPY RADAR Array and Signal Processor	Simulated AN/MPQ-53 Radar Atenna	Simulated TPS-75 RADARs (2)		
Missile		Simulated Standard Missile Blk 2 Flyout	Simulated GEM Missile Flyout	N/A	N/A	N/A
Launcher		Simulated	Emulated via Launcher Comm Controller Card	N/A	N/A	N/A

Tactical HWIL/SWIL

Project Office Supplied Simulations (Interceptor and Radar Front End)

DRAFT

Figure 3 TMDSE Build1 Tactical Systems

Theater Environment (TE) Functions

The TE, located within the TEC, is a real-time dynamic simulation of the physical environment (both natural and man-made) within which the TMD Systems are to operate. Physical phenomena include threat object propagation, TMD Systems locations (and location updates for mobile platforms), propagation of natural and man-made objects, and natural and hostile environments. The TE provides to TMD Systems only that information that the Systems would naturally perceive through their sensors or which affects their operational performance. By segregating simulation truth from TMD System perception, the TMDSE ensures that information not be available to the Tactical System under the circumstances being simulated do not bias the results of integration tests. Each TMD System must react to TE stimulus as that System would react in a real world situation. The threat and simulation scenarios and TMDSE initialization data specifically configure the TE for each test or exercise.

Test and Control (TC) Functions

The TC, also located within the TEC, provides the means by which the TMDSE controls itself as well as coordinates exercise event sequencing and timing with the Tactical Drivers. In addition, the TC monitors and records TMD System and component performance data and collects pre-mission and run-time data. Following completion of a test run, the TC also analyzes results and provides supporting data for test reports. The TC contains the TMDSE TCS operator interfaces, data bases, peripheral inputs and outputs, and instrumentation. The TC starts, stops, initializes, and resets TMDSE hardware, software, and Driver equipment. For TMD systems equipped to process external "test" commands, the TC will forward such commands through the Driver. The TC and other TMDSE functions also perform required maintenance operations.

TMD Tactical Drivers Functions

Each TMD Program Office (namely, PATRIOT, JTAGS, AEGIS, CRC, Talon Shield) provides a TMD Tactical Driver through which the TMDSE Control Segment will interface with their respective Tactical Systems. These drivers provide physical interfaces to the TMD Tactical Systems. The drivers receive TMDSE environments and control messages from the TMDSE Control Segment functions, and convert this data to a format and data rate that are usable by the tactical system. The drivers contain simulations of tactical components that are missing or impractical (for example, actual interceptors and radar antennas). The drivers also generate environment and scene data based on the TMDSE Control Segment inputs. Additionally, these drivers provide to the TCS data as perceived by the respective tactical systems.

The communication networks consist of a combination of local and wide area networks. These different networks interconnect the various TCS components, TMD Tactical Drivers, TMD Tactical Systems, and Tactical (or emulated tactical) Communication Networks (TCN). The communication networks are of two types: those that address the test control functionality and those that provide the tactical networks for the systems under test. Figure 4 provides an illustration of the Build 1 hardware configurations and their interconnections.

The TMDSE test control networks are high bandwidth (that is, T1 link) encrypted lines that join
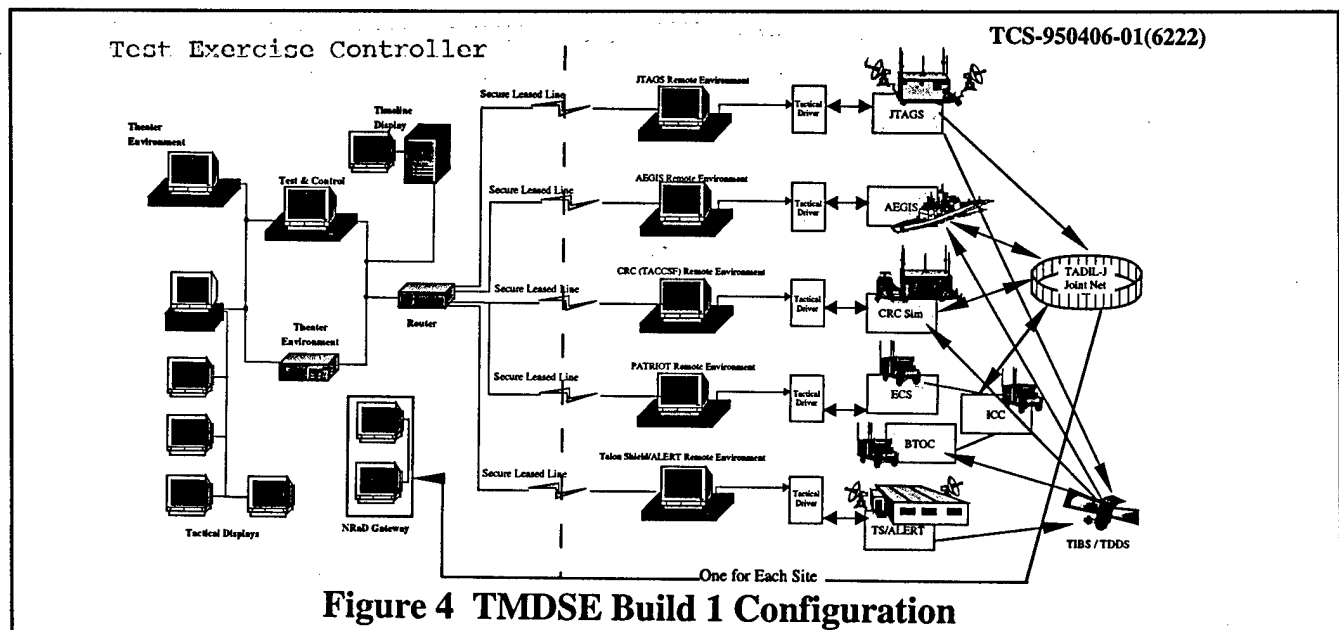

Figure 4 TMDSE Build 1 Configuration

the TEC in Huntsville at Teledyne Brown Engineering with all Remote Environments at each Tactical Driver site. Local Area Networks connect the Remote Environments to the Tactical Drivers. The network connections from the Tactical Drivers to the Tactical Systems built to be compatible with the Tactical Systems that they support.

The TCN connects the tactical systems to each other. These interfaces are the same communications expected of the TMD components with regard to protocol, message formatting, and routing selection. Figure 5 illustrates the Build 1 tactical communication links. In future builds, the interfaces to the TCN will include the TCS to actively monitor and stimulate activity on and through the network. For Build 1, the TCS passively monitors and displays tactical communication traffic using the U.S. Naval Command, Control, and Ocean Surveillance Center's (NCCOSC) Link 16 Emulator and Communications Monitor (the NRaD Gateway).

The NRaD Gateway provides the tactical communication link between the individual weapon systems emulating a Joint Tactical Information Distribution System (JTIDS). In addition, the simulated threat 'injected' into the JTAGS/Talon Shield systems generated real TIBS - TDDS cueing messages received by the PATRIOT, AEGIS, and CRC elements. The transmission of these TIBS and TDDS messages are by either live satellite broadcast, land line emulator, or a combination of the two.

TMDSE Application of DIS Protocols

The TMDSE Build 1 design includes the application of DIS protocol data units (PDUs) used between the Test Exercise Controller, the Remote Environments, and the individual tactical drivers. In addition, the TMDSE Build 1 configuration is a DIS-compatible test tool incorporating twelve (12) different PDUs listed in the Institute for Simulation and Training's (IST) "Standard for DIS - Application Protocols" Version 2.0, Fourth Draft (2.04). These 12 PDUs are: Entity State PDU, Acknowledge PDU, Fire PDU, Action Request PDU, Detonation PDU, Action Response PDU, Create Entity PDU, Data Query PDU, Start/Resume PDU, Stop/Freeze PDU, Data PDU, and Set Data PDU.
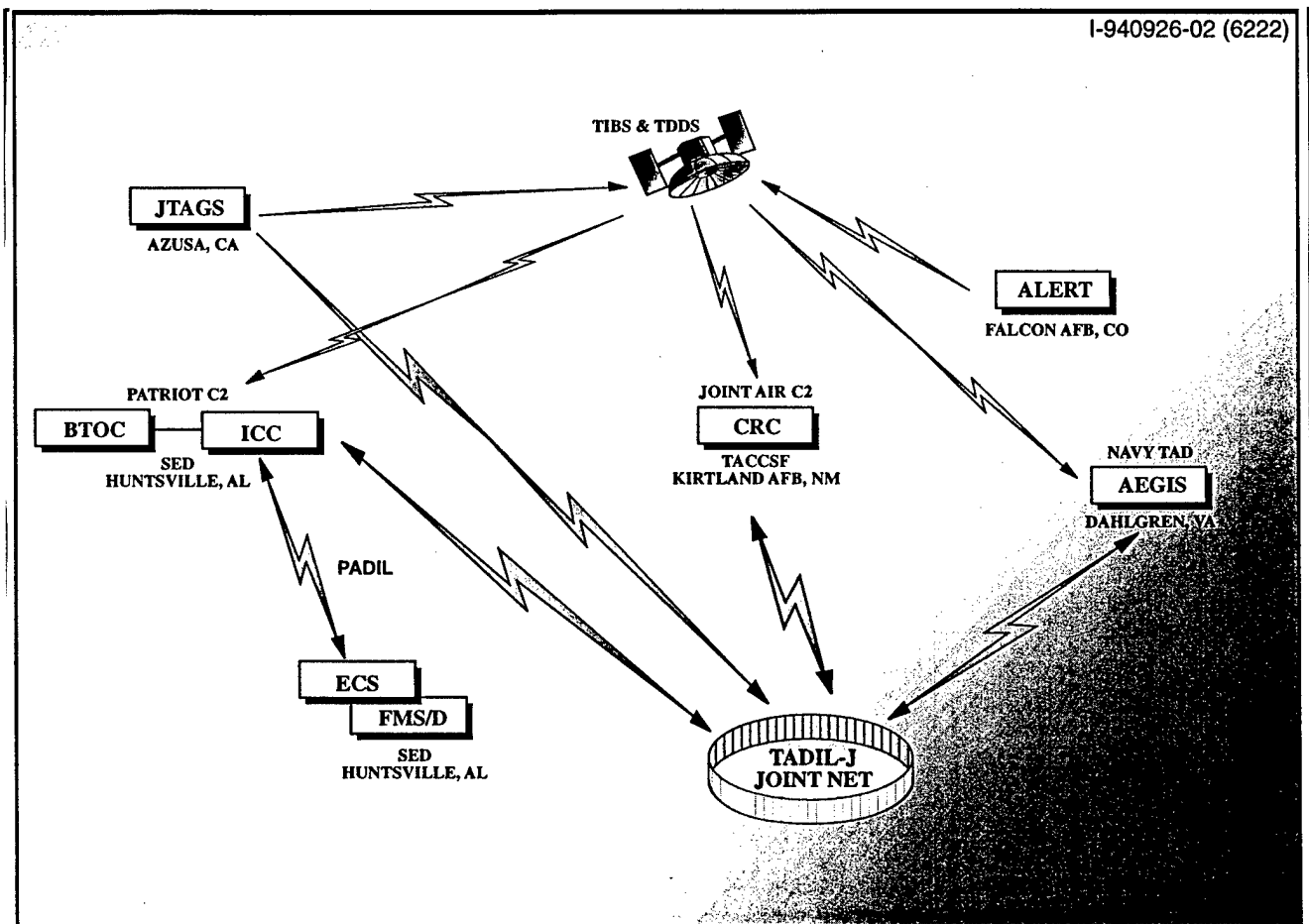

Figure 5 TMDSE Build 1 Tactical Communication Links

TMDSE Computer Hardware Configuration

The TMDSE execution environment is a heterogeneous configuration of workstations and associated operating systems. Sun Microsystems workstations running the Solaris 2.4 operating system accomplish the real-time aspect of the TCS. TMDSE graphic processing is primarily on Silicon Workstations running IRIX.

The Sun platforms are SparcStation 20s, Ultra Sparc's, and SparcServer 1000s. These are multiprocessing architectures with up to four processors on the SparcStation 20s and up to eight processors on the SparcStation 1000s. Each platform includes a GPS card for performing precise time synchronization among the widely distributed nodes. Ethernet interfaces handle communication between platform nodes with many platforms containing multiple Ethernet interfaces to support the TMDSE configuration.

The operating system installed on the Sun workstations is Solaris 2.4, a Sun version of UNIX. Solaris supports symmetric multiprocessing allowing programs to execute concurrently on several processors transparently. Solaris also includes POSIX compliant real-time extensions. These real-time extensions allow real-time, preemptive, time dependent applications such as the TMDSE to be effectively implemented on the Sun workstation environment.

The software for TMDSE is being primarily developed in Ada on Sun workstations. Current Source Lines of Code (SLOCs) estimates for the final Build 3 configuration of the TCS is around 200K lines. 90% of this code will be in Ada and 10% written in C. The Ada being used is the Sun IMPACT Ada. This Ada is a multi-threaded compiler that allows multitasking Ada programs to run on multiple processors in a truly concurrent manner. The Ada environment has a rich set of GUI tools that greatly enhance developer's productivity.

The TMDSE 2-D map displays as well as Test and Control displays execute on the Sun workstations using both monitors and x-terminals. All display software run on Sun workstations is in Ada. The Silicon Graphics workstations are primarily for high resolution 3-D graphics displays. Display software run on Silicon Graphics workstations is in both Ada and C where required. Both 2-D and 3-D displays are X-Window Motif based graphics.

D-HWIL Benefits

Identification of issues and shortfalls in system performance early in development process is critical so that resolution is more cost effective. Figure 6 provides a graphic illustration of this benefit. D-HWIL testing allows developers to evaluate what effects an operationally realistic environment has on early prototypes of developmental systems. It provides a robust test environment with representative numbers of threat vehicles and equipment, plus the suite of friendly C4I and weapon systems with which a system under test would interact. These early assessments allow for more complete testing during development including environments that are not feasible in field tests. In addition, D-HWIL enhances test planning by helping to determine which range tests are the most critical and

Figure 6 Cost benefit of early problem identification

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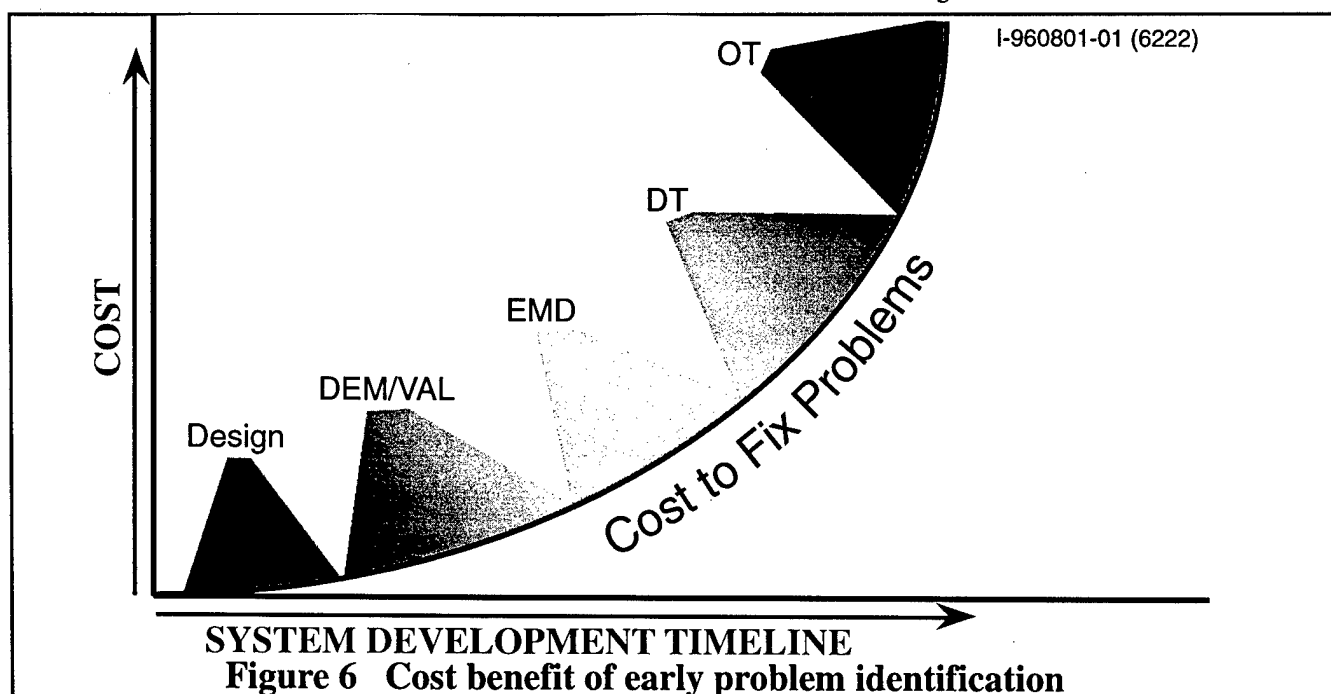
thereby allowing the program to conserve scarce test resources.

Establishing standardized interface applications during initial development reduces cost. This approach allows early interoperability testing using HWIL simulators linked with the other players representative of the intended theater of operations. This realistic loading on equipment and personnel achieved using D-HWIL is necessary to accurately assess the tactical system's capabilities in the field. This also allows the early evaluation of tactical operator interactions as well as opportunities for extensive training over a wide range of operational scenarios.

One of the other major benefits in combining both HWIL and real time system-level simulations is developing confidence in the representative models and simulations (M&S). These M&S are critical to the TMD FoS acquisition process since they must generate the bulk of the performance data used by the evaluators. Previous experience has shown the importance of planning and executing verification, validation, and accreditation (VV&A) activities as early as possible for each major system. A successful VV&A program for BMD systems requires that all of T&E activities build a consistent and synergistic evaluation data base. To accomplish this objective, it is vital that all T&E activities have the structure and compatibility in terms of test scenarios, environmental conditions, and operational concepts afforded by using D-HWIL.